Gamma Ray Energy Measurement using the Multiple Compton Technique

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Abstract

Modern developments in detector and electronics technology now enable a new generation of gamma ray detectors based on recording each and every energy loss associated with an incident gamma ray. The energy of an incident gamma ray is determined by measuring the positions of the first three interactions, and the energy loss of the first two. The direction of the incident gamma ray is restricted to a conical range of possible directions. The significance of such a detector is at least three-fold: First, a gamma ray need not be totally absorbed in order to measure its full energy. Thus, relatively thinner detectors are possible. Detection efficiencies approaching 40% at 1 MeV are possible in a silicon detector system of only 40 g/cm^2 thickness. Second, these detectors are naturally imaging without the need for a complex aperture or collimator. Third, these detectors have little or no Compton shelf, thus Compton rejection or heavy shielding is no longer required. We report on a simple demonstration measurement using three position sensitive detectors.

I. INTRODUCTION

Traditional gamma ray detectors completely absorb the energy of a gamma ray in order to determine its energy.   A gamma ray may interact several times within a detector before either being absorbed in a photo-electric interaction, or possibly escaping the detector. Those gamma rays that escape lead to features such as a Compton shelf below the full energy peak.

A more sophisticated detector is the Compton telescope, which observes an initial scattering interaction in one position-sensitive detector, then absorbs the scattered energy in a second detector. The Compton telescope has imaging capabilities. However, it too must capture the full energy of the scattered gamma ray to provide the desired energy measurement.   Partial absorption events contribute to a Compton shelf and are not imaged properly to the source.

An alternative detection technique is possible by independently measuring the positions and energy loss of each interaction [1,2]. Consider a gamma ray that enters a three-dimensional imaging detector and undergoes two Compton scatters, followed by a third interaction of any type. The energy of this gamma ray is uniquely determined by measuring the energies of the first two interactions, and the positions of the first three interactions (*i.e.* measure the scatter angle of the second interaction). In essence, the Compton scattering formula specifies the energy of a gamma ray before a scatter, given the energy lost in the scattering event and the angle of scatter. It is not necessary to totally absorb all of the energy of the event in order to measure its energy. Precise position and energy measurements are essential for an accurate energy determination.   We call this the three-Compton technique, representing the need for three interactions.

Three-Compton has several unique properties.   The efficiency at energies in the Compton regime (roughly 0.1-10 MeV) can be substantially higher than a traditional detector of similar mass, since it is not necessary to totally absorb the event. This can be a substantial advantage in a low source strength, background-dominated application such as gamma ray astronomy. Further, the three-Compton detector is an imaging device in exactly the same manner as a traditional Compton telescope. The possible source for each incident gamma ray is restricted to a cone determined by Compton kinematics. The cone axis is defined by the direction of the first scattered gamma ray, and the half-angle is the scattering angle determined by the energy loss at the scattering site [3,4]. The superposition of many such "cones" may be used to reconstruct an image of a source region. Finally, the Compton shelf is highly suppressed, thus reducing the need for heavy anticoincidence shielding required in some applications.

The Compton shelf is not eliminated in a practical three-Compton detector. Passive material within or nearby the detector provides a mechanism in which one of the critical first interactions goes undetected or is misidentified. It is also necessary to correctly sequence the first three interactions in the order in which they occur [5,6]. These issues can be improved by measuring four or more interactions, and by applying analysis to select the most probable of the various combinations of possible event orders.

II. EXPERIMENT

A simple 3-Compton demonstration was performed with two position-sensitive detectors and a third detector that were available in our laboratory.   The two position-sensitive detectors used were germanium strip detectors, housed in two separate cryostats.   The third detector was a scintillator coupled to a photomultiplier tube. The configuration of the experiment is shown in Figure 1. The D1 detector was a germanium strip detector with an active volume measuring 5x5x1 cm^3. The detector has 25 strips on each face that are used to determine positions of each interaction with a 2 mm position resolution in two dimensions. The uncertainty in the depth of the interaction is essentially the 1 cm thickness of the detector. D2 consists of four germanium strip detectors in a common cryostat (Figure 2). Each detector is identical to the single detector in D1. The detectors are arranged in a 2x2 array with a small gap between them. The D1 and D2 are designed to have thin windows both in front of and behind the
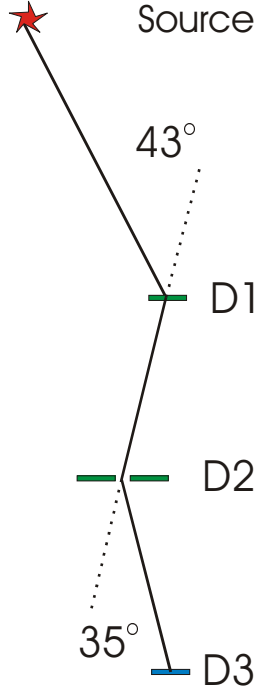
Figure 1: Experimental configuration for the 3-Compton demonstration. Detectors and positions are drawn roughly to scale. The direction of the source is indicated, but the true position is 122 cm from D1.

Figure 2: Photograph of the D2 detector, which consists of a 2x2 array of germanium strip detectors in a common cryostat.

detectors; thus, partially absorbed (*i.e.* scattered) gamma rays have a high probability of escaping without interacting in surrounding passive materials. D3 uses a 4 mm thick CsI scintillator with an area of 4 x 2 cm. Spacing of the detectors in the direction normal to their surfaces were 23 and 26 cm respectively. A 10 mCi ^{137}Cs source (662 keV) was placed 122 cm from D1 illuminating it at 27 degrees from normal incidence. Typical scatter angles connecting the detector centers are 43 degrees and 35 degrees respectively.

The detector readout was performed with NIM shaping amplifiers and logic, and with CAMAC ADCs and discriminators. The full system employed 147 spectroscopy-channels with list-mode readout, and was controlled by a PC.

A three Compton telescope composed of small detectors has a very low efficiency, making this experiment challenging. The principle source of background was from chance coincident events. Accidental rates were minimized by collimating the source, and by lead shielding that minimized direct and scattered radiation from reaching detectors D2 and D3. In spite of best efforts, the event rate in D2 was still half that of D1, albeit it has four times the area. Presumably, much of the D2 event rate was scattering of the primary beam off of passive material in or near the D1 cryostat which could not be avoided. True double-Compton coincidence events scattered from D1 represent an estimated 3% of the total D2 rate. The measured 3-Compton event rate was 0.35 Hz, compared to a calculated chance coincidence rate of 0.12 Hz in a 1-microsecond coincidence window, and an estimated 0.15 Hz for the true coincident events. The discrepancy is small and well within the errors of these estimates. Thus, roughly half of the events recorded are background.
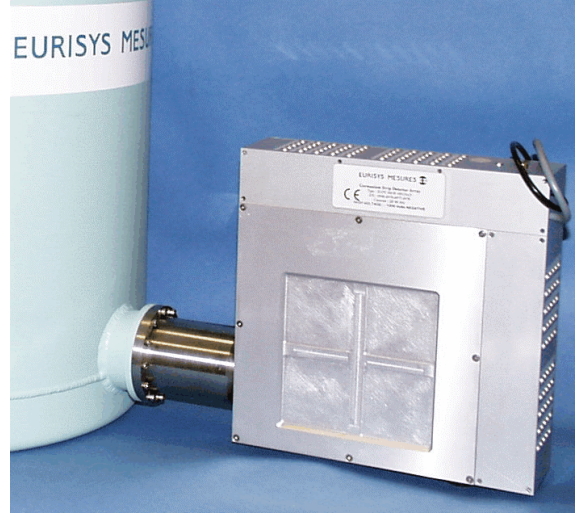
The energy loss in D3 is not needed for reconstructing the energy of each event. The basic measurement uncertainties are, energy losses in the D1 and D2 detectors (2 and 3 keV FWHM respectively), position resolution of the two germanium detectors, precise knowledge of the positions and orientation of the detectors within their cryostats, and the size of the D3 scintillator. Translational and rotational degrees of freedom have been studied in the data analysis and can be measured to some degree. However, residual uncertainties in determining positions on the order of 2 mm in each direction seem likely.

It is also significant to note that the discriminator on D2 was set at 30 keV due to higher noise levels on a few strips. The most probable energy loss in D2 is ~70 keV, however small scattering angles less than about 21° were not detected because the corresponding energy loss is below this discriminator.

The energy of the incident gamma ray, E_i, is fully determined from the first three interactions by,

$$E_i = \Delta E_1 + \frac{\Delta E_2 + \sqrt{\Delta E_2^2 + 4\Delta E_2 m_e c^2 /(1 - \cos\theta_2)}}{2}, \qquad (1)$$

where ΔE_1 and ΔE_2 are the energy losses in the first two detectors, and θ_2 is the scatter angle of the second interaction [1]. The angle θ_2 is determined by the interaction positions measured in detectors D1, D2, and D3, shown in Figure 1 to be on the order of 35°. The right-hand term of this equation is an expression for the energy of the gamma ray incident on the D2 detector (*i.e.* scattered by D1 into D2). It depends only on the scatter angle and energy lost in D2. The left-hand term simply adds the D1 energy loss to determine the energy incident on D1.

The D3 detector did not provide useful position information. However, the basic 3-Compton principle of
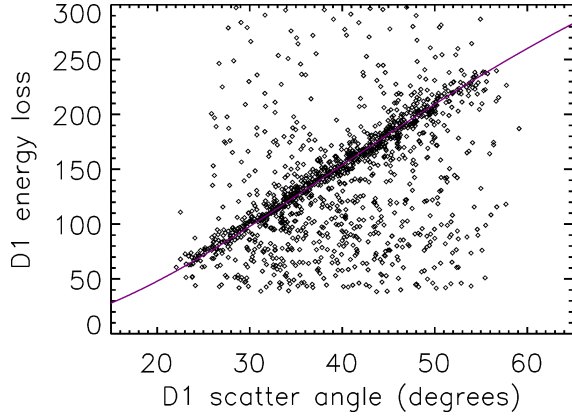
Figure 3: Scatter angle θ_1 vs. D1 energy loss. The solid line is the prediction based on the Compton formula for comparison.

Figure 4: Distribution of the D1 energy loss about the prediction for Compton scattering.

reconstructing energy is demonstrated in a simpler experiment using only the first two detectors. The scatter angle, θ_1, is determined by using the known position of the source (possible in a laboratory test), rather than an upstream detector as required by equation (1). The energy of the incident gamma ray is determined by,

$$E_i = \frac{\Delta E_1 + \sqrt{\Delta E_1^2 + 4\Delta E_1 m_e c^2 /(1 - \cos\theta_1)}}{2}, \qquad (2)$$

where θ_1 is determined by the known position of the source, and the positions measured in D1 and D2. As before, the energy of the incoming gamma ray is determined without requiring total absorption.

III. RESULTS

The D1 and D2 detectors make a traditional Compton telescope with several desirable properties. The probability of multiple interactions within a single imaging element in the detector, *i.e.* the voxels defined by the intersection strips on the two faces of the detector, is quite small. Events with energy losses that are not contained in a single voxel are vetoed in this analysis, thus the vast majority of the data represents a single interaction in D1 and a single interaction in D2. The single voxel screening results in a roughly 20% loss in efficiency for each detector at these energies since a thin gap region between strips share charge collection between the neighboring strips [7]. Most of these edge events could be recovered with a more detailed analysis, but this is not necessary for this work. Requiring D3 in the trigger criteria has no significant effect on the performance of the D1/D2 Compton telescope, other than to ensure that none of the events loose all their energy in D1/D2.

Figure 3 shows the measured energy lost in the first scatter as a function of measured scatter angle. The majority of events cluster along a line corresponding to Compton scattering of 662 keV gamma rays. Events above and many of the events below this line are chance coincidence events between the two detectors. The scatter in the data about the model is due to uncertainties in the position and energy measurement, but also due to Doppler broadening [8].
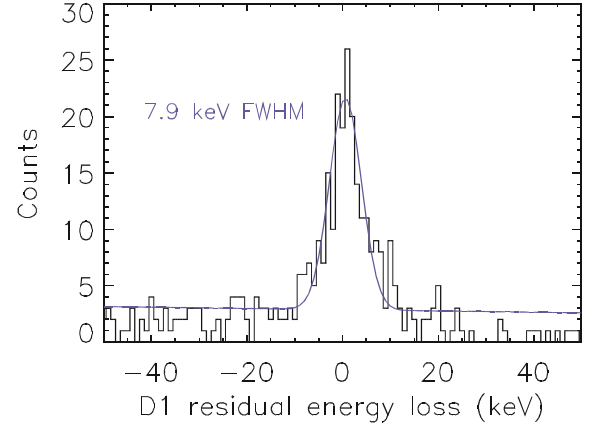
Doppler broadening is estimated to contribute approximately 4.6 keV FWHM additional broadening to the D1 energy loss.

The difference between the measured D1 energy loss and that predicted by Compton scattering is shown in Figure 4. These data are selected to include only one of the four detectors that comprise D2 in order to minimize broadening due to uncertainties in the detector positions and orientation. The selection of detector within D2 affects the peak position by a slight shift from zero, but there is no significant change in peak width. The width of the residuals is 7.9 keV FWHM when using a single detector in D2, *vs.* 13 keV FWHM when all four detectors are included. In principle these peaks can be aligned and the width minimized by introducing corrections for the three translational and three rotational orientations of each detector. There are a total of 30 degrees of freedom in the system. For this analysis, the translational positions of both D1 and D2, a total of six degrees of freedom, were allowed to vary in steps of 1 mm to search for a minimum peak width. Errors between the measured and optimized detector positions were about 4 mm, indicating the location uncertainties of the detectors within the cryostat.

The components to the peak width include energy resolution (2.0 keV FWHM), angular measurement error due to the size of the voxels (3.8 keV FWHM), and Doppler broadening (4.6 keV FWHM). The rms combination of these terms predicts a width of 6.3 keV FWHM. An additional broadening term on the order of 4.8 keV FWHM is required to explain the width observed in Figure 4. Presumably, this is dominated by the positional uncertainties of the detectors.

The energy spectrum of the incoming gamma rays from the ^{137}Cs source is reconstructed using Equation 2, and shown in Figure 5. The spectrum consists of three components: the reconstructed 662 keV peak, a background from chance coincidences, and a shelf below the peak. The shelf is cut off at low energies by the discriminator levels of the detectors and the restricted geometry of the experiment, thus it is impossible to reconstruct an energy below about 200 keV with the configuration of detectors used here (lower energy sensitivity would require larger scatter angles or lower discriminator settings).

The Compton telescope should not have a "Compton-shelf," typical of calorimeter type detectors. The observed
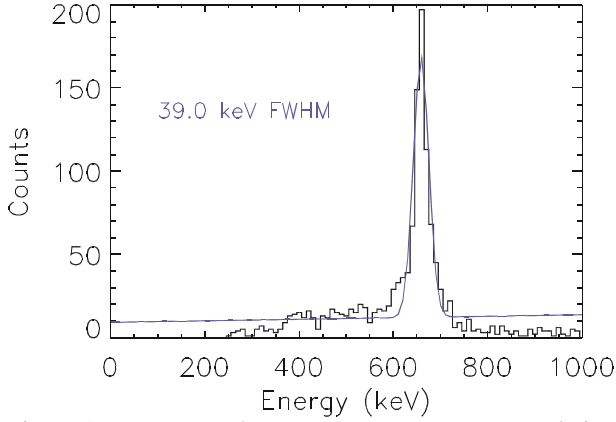
Figure 5: Reconstructed energy spectrum. Energy resolution of the 662 keV peak is 39 keV FWHM.

Compton-shelf is produced by gamma rays that scatter, but then exit the detector resulting in only a partial energy loss. This experiment does not depend on capturing the gamma ray, thus there should be no appreciable Compton shelf. Every event that is not a chance coincidence or other less probable occurrence should reconstruct to the full and proper incoming energy. The low energy shelf below the peak is attributed to down scattering of 662 keV gamma rays in the source and source holder. Thus, the spectrum in Figure 5 accurately reflects the true emission from the source without the need for corrections or deconvolution of a complex detector response.

The peak width is 39 keV FWHM, which is in reasonable agreement with 45 keV FWHM derived from an error analysis of Equation 2, assuming 13 keV FWHM for the uncertainty in ΔE_1 (scatter in Figure 3), and 0.7° FWHM for the uncertainty in θ_1 (Monte Carlo estimate based on voxel sizes and spacing).

IV. DISCUSSION

The 3-Compton concept is being developed for astrophysics and terrestrial applications that require high efficiency, low backgrounds, and imaging in a single instrument. The efficiency improves dramatically if the small detectors used in this work are replaced by large arrays, and if the instrument is comprised of a thick stack of these arrays as shown in Figure 6. An instrument might consist of germanium or silicon strip detectors, or possibly a noble-gas imaging time projection chamber [9].

It is important that the angle determined by the position resolution of the detector over the mean distance traversed by a scattered gamma ray is small. Uncertainty in this angle defines the ultimate energy and angular resolution that the instrument can achieve, but the Doppler broadening effect defines the limiting resolution that is possible. Doppler broadening is minimized in a low-Z material such as silicon [8]. Typically, this angle should be less than about one half degree for silicon, or a degree in germanium.

An Advanced Compton Telescope composed of 5-mm thick silicon detectors stacked with a 10 mm pitch has a mean scattering distance on the order of 10 cm for typical gamma rays >400 keV. The depth of an interaction can be determined by observing pulse rise times as described by [10]. The

corresponding 3-dimensional position resolution of ~1 mm is optimal, providing angular resolution limited by the Doppler broadening and not the positional uncertainty of the devices. The optimization for lower energies or other detector configurations varies slightly. The energy resolution provided by silicon detectors (<2 keV FWHM with practical CMOS readout electronics) is slightly smaller than the Doppler broadening term, thus Doppler broadening is the limiting factor for the energy resolution that can be achieved in a silicon-based 3-Compton telescope.
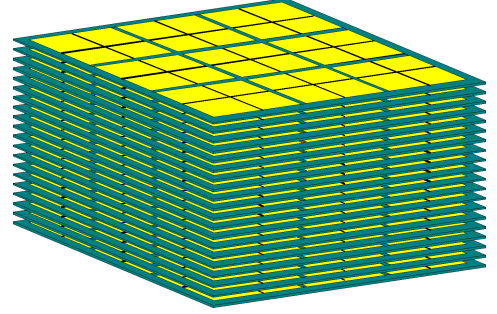

Figure 6: Conceptual design of an Advanced Compton Telescope using the 3-Compton principle.

The efficiency of such a detector can exceed a conventional calorimeter of similar mass because there is no requirement to capture all of the energy. Monte Carlo simulation of an instrument that is 40 g/cm^2 thick silicon with a 100x100 cm^2 frontal area finds that the efficiency is ~30% at 1 MeV, assuming that 80% of the material in the detector is active. The size of the simulated instrument was chosen to achieve the large collecting area that is required in gamma ray astronomy.

V. CONCLUSION

The 3-Compton telescope principle can be applied using modern position-sensitive detectors in a practical system. It is important that these detectors make both good energy and position measurements of each interaction. These requirements can be realized in silicon or germanium strip detectors that are available today. The energy resolution of silicon approaches that of germanium, and is good enough that Doppler broadening is the limiting factor for performance. Silicon offers the advantage of less Doppler broadening than other applicable detection media, including Ge, CdZnTe, Xe, Ar, and inorganic scintillators to name a few. It also has the potential of higher operating temperatures than germanium, which may make implementation of a large system easier.

VI. ACKNOWLEDGMENTS

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